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ABSTRACT
Fouling of fin-and-tube heat exchangers by particle deposition leads to diminished effectiveness in supplying ventilation and air conditioning. This paper explores mechanisms that cause particle deposition on heat exchanger surfaces. We present a model that accounts for impaction, diffusion, gravitational settling, and turbulence. Simulation results suggest that some submicron particles deposit in the heat exchanger core, but do not cause significant performance impacts. Particles between 1 and 10 μm deposit with probabilities ranging from 1 - 20 % with fin edge impaction representing the dominant mechanism. Particles larger than 10 μm deposit by impaction on refrigerant tubes, gravitational settling on fin corrugations, and mechanisms associated with turbulent airflow. The model results agree reasonably well with experimental data, but the deposition of larger particles at high velocities is underpredicted. Geometric factors, such as discontinuities in the fins, are hypothesized to be responsible for the discrepancy.

INDEX TERMS
HVAC, Fouling, Modeling, Heat exchangers, Experiments.

INTRODUCTION
Fouling of heat exchangers can cause significant energy and indoor air quality degradation for heating, ventilating, and air conditioning (HVAC) systems. Particulate fouling of indoor fin-and-tube heat exchangers, particularly air conditioner evaporators, is especially important because space cooling in buildings is an important contributor to overall energy use and peak electricity demand (Krafthefter *et al.*, 1987). Furthermore, microorganisms can colonize persistently moist surfaces of cooling coils, causing indoor bioaerosol problems (Hugenholtz and Fuerst, 1992; Morey, 1988).

Although cleaning and maintaining heat exchangers is discussed extensively in technical reports, trade journals, and manufacturers' literature, little has been written about the factors that control heat-exchanger fouling by particle deposition (Muyshondt *et al.*, 1998). The purpose of this paper is to develop and verify a model of particle deposition in typical HVAC heat exchangers so that the potential energy and indoor air quality effects can be evaluated. The model is simple and general enough that it can be applied to a wide range of heat exchangers. The purpose is to use three major inputs (air velocity, particle size, and fin spacing) and several minor inputs to determine the likelihood that a particle will deposit in the heat exchanger. The paper also summarizes laboratory experiments that have been performed to validate the model.

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HEAT EXCHANGER DESCRIPTION

The HVAC heat exchangers of interest are designed to exchange energy between a refrigerant and an air stream that is in turn used to condition an indoor space. Typical heat exchangers consist of horizontal refrigerant tubes with attached thin vertical fins to increase heat transfer. A typical residential heat exchanger has two staggered sets of 0.95 cm copper refrigerant tubes that run horizontally through vertical aluminum fins. Commercial and industrial systems can have much larger tubes. Fin spacings range from 2.4 to 7.1 fins/cm, with typical systems having 4.7 fins/cm. The fins are approximately 100 µm thick and are often corrugated to increase surface area for better heat transfer. Heat exchanger depth can vary, but typical residential and small industrial and commercial heat exchangers are about 5 cm thick and are often grouped together for larger capacities. Air velocities range from 1 to 5 m/s in these systems.

MODELING PARTICLE DEPOSITION

For the purposes of modeling, the heat exchanger geometry is reduced to a series of straight channels created by the fins with cylindrical refrigerant tubes that run horizontally, perpendicular to the fins. The particle deposition model accounts for impaction on refrigerant tubes and fin leading edges, Brownian diffusion in fin channels, gravitational settling on fin corrugations, and air turbulence effects.

Anecdotal descriptions of fouled heat exchangers suggest that impaction on the leading edge of the fins is an important mechanism. For this analysis we assume that the fin edge is a blunt body and use Hinds' (1999) analysis for cascade impactors with a modification to account for the fraction of face area of the coil that is taken up by fin edges. The penetration fraction because of impaction on fin edges is estimated as follows:

$$P_{fin} = 1 - \left(Stk_{eff} \frac{\pi}{2} \right) \frac{t}{w} \tag{1}$$

Where Stk_{eff} is the particle Stokes number based on the duct air velocity and the fin thickness, corrected for particles having particle Reynolds numbers > 1 (Israel and Rosner, 1983), t is the fin thickness, and w is the fin spacing. The term in the parentheses is limited to a maximum value of one.

Particles also impact on refrigerant tubes that run perpendicular to the air flow direction and the fins. There are several theoretical and experimental studies of particle impaction on tubes. An extension of the analysis of Israel and Rosener (1983) suggest the following formula for estimating penetration for flow past a network of tubes:

$$P_{tube} = 1 - \left(1 + 1.25 \frac{1}{a} - 0.014 \frac{1}{a^2} + 0.508 \times 10^4 \frac{1}{a^3} \right)^{-1} \frac{d_{tube}}{w_{tube}} n_{tube} \tag{2}$$

Where a is $Stk_{etf,tube}$ – 1/8 ($Stk_{eff,tube}$ is the particle Stokes number based on the air velocity in the heat exchanger and the tube diameter), d_{tube} is the refrigerant tube diameter, w_{tube} is the center-to-center tube spacing, and n_{tube} is the number of sets of tubes in the direction of flow. The term in the square brackets is limited to value of ≤ 1 and the d_{tube}/w_{tube} ratio is added to limit the deposition to particles in the volume of air directly in front of the tubes.

To increase heat transfer, manufacturers often corrugate fins. Large particles can deposit by gravitational settling on the corrugation ridges. Penetration fraction due to gravitational settling (Fuchs, 1964) is estimated as:

$$P_G = 1 - \left(\frac{V_s z}{hU}\right)\frac{y}{(w-t)} \tag{3}$$

where V_s is the particle settling velocity, z is the heat exchanger depth in the direction of bulk air flow, h is the average height of the fin corrugations, U is the bulk air velocity in the heat exchanger, and y is the peak to trough corrugation width.

Air turbulence in the duct leading up to a heat exchanger can also induce deposition. The fluctuating components of velocity can impart an angled trajectory to particles as they enter the heat exchanger. If the particle has a sufficiently large relaxation time and a sufficient deviation in velocity direction from the bulk flow, it will impact on a fin and not penetrate the coil. Mathematically, we estimate the penetration associated with turbulence as:

$$P_T = \text{Prob}\left(\frac{\tau_{imp}}{\tau_{rel}} > 1\right) \tag{4}$$

where τ_{imp} is the characteristic time for a particle to impact on the wall and τ_{rel} is the particle relaxation time (Hinds, 1999). A Monte Carlo simulation was used to estimate P_T. In the analysis, particles were assumed to enter the channel uniformly distributed between the fins. The fluctuating components of the air velocity were assumed to be independent Gaussian distributions whose shape, as a function of bulk velocity in the duct, comes from direct numerical simulation (DNS) data presented by Moser *et al.* (1999).

Small particles are likely to deposit by Brownian diffusion. The penetration fraction due to Brownian diffusion is calculated assuming laminar flow in the heat exchanger core and follows the work of DeMarcus and Thomas (1952):

$$P_D = 0.915e^{(-1.885\phi)} + 0.0592e^{(-22.3\phi)} + 0.0259e^{(-152\phi)} \tag{5}$$

where $\phi = 4Dz/(w-t)^2U$ and D is the particle diffusion coefficient.

The deposition mechanisms are combined assuming that they operate independently so that the overall deposition fraction, η, is estimated by the following expression. The assumption of independence is well justified for mechanisms that affect widely different particle sizes, such as Brownian diffusion and gravitational settling (Chen and Yu, 1993). The assumption has been applied to estimate deposition by combined mechanisms in other cases, such as fibrous filtration (Hinds, 1999).

$$\eta = 1 - P_{fin}P_{tube}P_G P_T P_D \tag{6}$$

EXPERIMENTAL METHODS

Experiments were conducted to verify the modeling work using the apparatus depicted in Figure 1. Monodisperse particles, tagged with fluorescein, were generated with a vibrating orifice aerosol generator (TSI model 3450) and then charge neutralized (TSI model 3054). Air from the particle generator was diluted with HEPA-filtered air and sent into 24 m of straight 15 cm square duct. Several honeycomb flow straighteners were used to promote fully developed turbulent flow with a uniform concentration of test particles. The particle-laden air then passed through an experimental 4.7 fin/cm heat exchanger that entirely fills the duct. The test heat exchanger is typical of those found in residential and light commercial buildings.

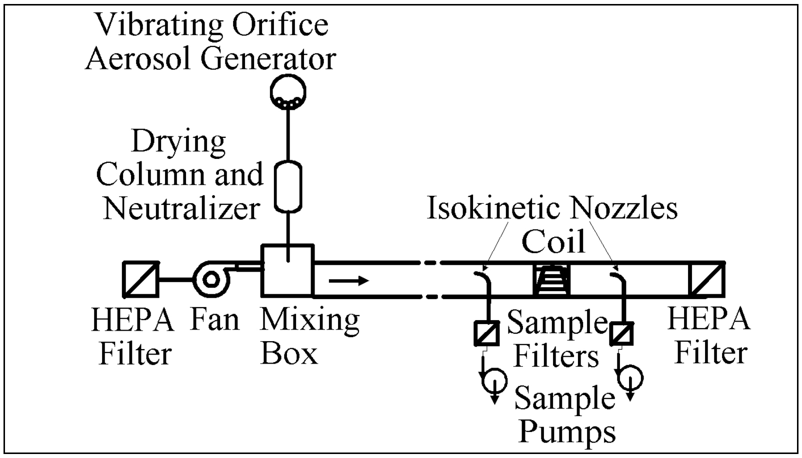

Figure 1. Experimental apparatus.

The particle size was determined with an aerodynamic particle sizer (TSI model 3320). Airborne particle concentrations were measured upstream and downstream of the heat exchanger by isokinetically sampling the air onto filter paper, which was later analyzed by fluorometric techniques (Turner Designs model TD-700 fluorometer). The coil and the filters were washed repeatedly with sodium phosphate buffer until there was no measurable amount of fluorescein remaining on the coil surfaces. The deposition fraction was calculated as the mass deposited on the coil divided by the product of the average upstream concentration and the total volume of air passing through the coil.

RESULTS

Figure 2 shows the modeling results for different fin spacings and air velocities. The model predicts that particles are more likely to deposit for denser fin spacings, which cause more fin edge impaction, increases fin corrugation area for gravitational settling and reduces the lateral distance particles must travel before depositing on fin surfaces. Lower velocities cause more deposition by Brownian diffusion and gravitational settling. Higher velocities cause more deposition by impaction on fins and tubes and inertial turbulent impaction. The kinks in the deposition fraction curves in Figure 2 (at 2 – 8 µm, depending on velocity and fin spacing) are caused by the removal of all particles directly in front of the fins by fin edge impaction.

Figure 3 compares modeled and measured deposition fractions for two air speeds. Horizontal error bars indicate one standard deviation in particle size and vertical error bars indicate the predicted uncertainty by propagation-of-error analysis. The modeled deposition fraction for the 1.5 m/s air speed (left) shows reasonable agreement with the measurements. Modeled deposition fractions for the 5.2 m/s airspeed (right) shows good agreement with data for smaller particles, but underpredicts deposition for larger particles.

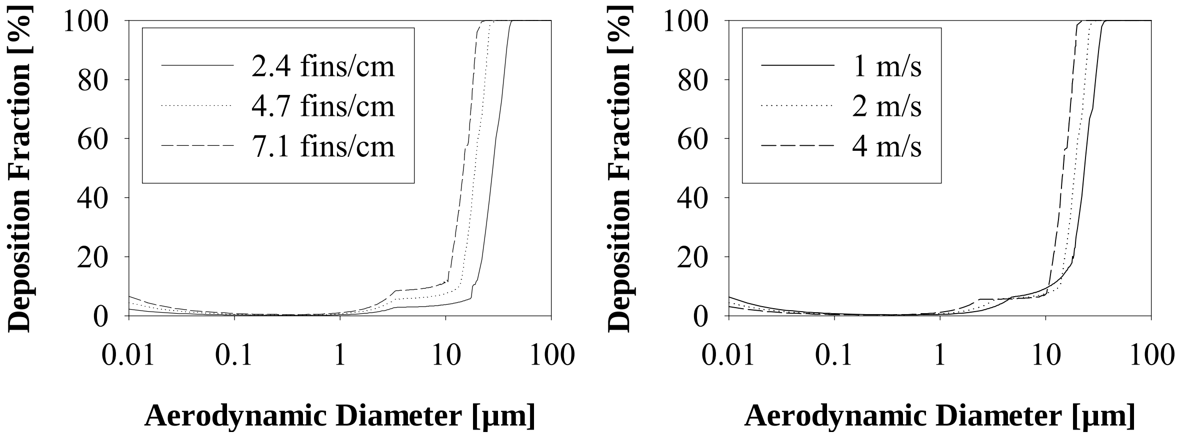

Figure 2. Modeled deposition percentage versus fin spacing (left) and bulk air speed (right).

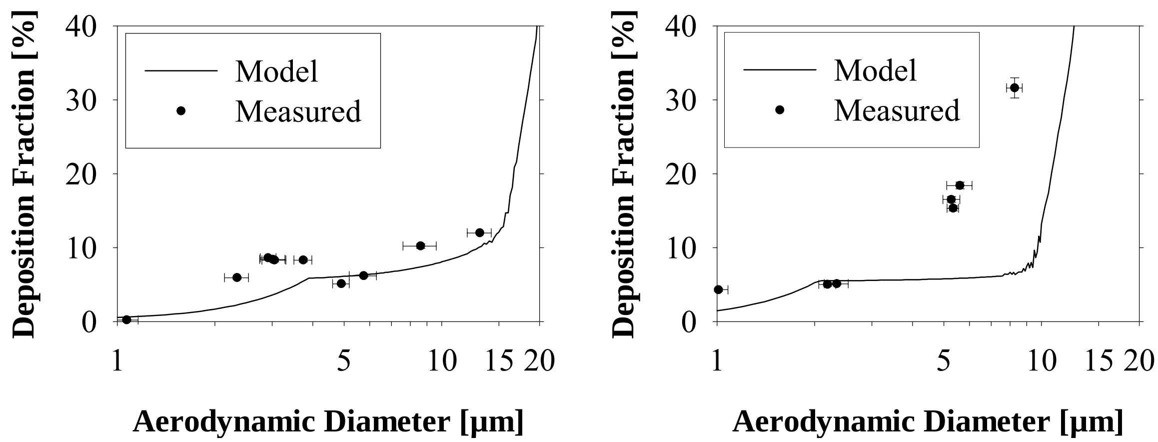

Figure 3. Modeled and measured deposition percentages for 1.5 m/s (left) and 5.2 m/s (right).

DISCUSSION

The results presented in Figure 2 are roughly consistent with published results from computational fluid dynamic simulations of Muyshondt *et al.* (1998). Despite some minor differences in details, the present modeling work agrees with the conclusion of earlier work that heat exchanger fouling is probably caused by larger particles.

The experimental results in Figure 3 suggest that the model slightly underpredicts deposition of all particles at low velocities and more significantly underpredicts deposition of large particles at high velocities. Much of the sharp increase in the modeled deposition fraction that occurs at 10-20 µm is caused by inlet turbulence. One possible explanation for the model-measurement discrepancy for large particles at the high velocity is that the turbulence data used in the Monte Carlo simulation has smaller velocity fluctuations than was present in the experiments. Another possibility is that the criterion used for deposition in Equation 4 is too stringent. A possible cause of underprediction at both velocities is that the fin spacings are modeled as smooth channels, but real heat exchangers, including the test heat exchanger, have many discontinuities in the fins that provide additional deposition sites.

SUMMARY

Modeling coils with fin spacings of 2.4 to 7.1 fins/cm and incident airspeeds of 1 to 5 m/s suggests the following general conclusions. Deposition of very small (submicron) particles is typically very low (i.e. < 5%) and is predominantly caused by Brownian diffusion. Although particles of this size are common in indoor environments, this low deposition rate and their small size suggests that they are unlikely to result in significant heat exchanger performance degradation. Particles in the range of 1 - 10 µm, which includes some soil grains, common bioaerosols, and particles from cooking, are likely to deposit on the leading edge of the coil by impaction, with minor contributions to deposition from the other mechanisms. Over the range of fin spacings and airspeeds of interest, deposition fractions of 1 – 10 % are common in this particle size range. Very large particles, with diameters from 10 – 100 µm, such as those found in ordinary indoor dusts (Hinds, 1999), are likely to deposit by turbulent impaction, by gravitational settling in the corrugated channels of the fins, and by impaction on refrigerant tubes in the core of the heat exchanger. These particles probably contribute significantly to the bulk of fouling because of their large size and high deposition fraction. Low filter efficiency, poor filter installation or duct leakage after the filter in the return duct of an HVAC system can permit these large particles to be present in the air upstream of coils.

Experimental data suggest that the model can provide reasonable predictions of experimentally measured deposition fractions. Given the potentially serious indoor air quality and energy impacts that result from HVAC heat exchanger fouling, it is useful to conduct additional experimental and modeling work to quantify the energy and air quality effects of heat exchanger fouling caused by the deposition of airborne particulate matter.

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